Cross-Layer Design For Large-Scale Sensor Networks

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Ananthram Swami
US Army Research Lab
aswami@arl.army.mil
Adelphi, MD, 20783
USA

Lang Tong
Cornell University
ltong@ece.cornell.edu
Ithaca, NY 14853
USA

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Network Overhead is Costly!

- Network Functions Are Dominant Users of Bandwidth
- Fixed Overhead Increasingly Less Efficient as Duty Cycle Decreases
- Closed Loop Mechanisms Require Duplex Operation
- Much of Bandwidth Provides Redundant/Unnecessary Information
  - Headers for Each Level
  - Timing
  - Status

Redundant since information exists in the Integrated system

SUOSAS Aggregate 200 Mbps Capability

512 byte packet, 32 mcps & FEC = 1/2 @ 4000 kbps maximum burst	Bits (in K)	Reduction	% Payload
Transmission Capacity of 50 Radios	200,000		
Half-Duplex Operation	100,000	100,000	
Channel Contention @ 5 Radio Density	40,000	60,000	
UDP Header	39,385	615	34%
IP Header	37,647	1,738	95%
COMSEC Header	36,571	1,076	59%
Radio Network Header	36,120	451	25%
Radio Link Layer Header	35,679	441	24%
Modem Framing & CRC	35,068	611	34%
Forward Error Correction	17,534	17,534	
Waveform Framing	17,491	43	2%
Synchronization Probe Overhead	13,378	4,113	226%
Slot Quantization @ 1.2 ms per Slot	11,378	2,000	110%
Channel Acquisition (RTS/CTS)	6,827	4,551	250%
Frame Acknowledge	5,689	1,138	62%
Average Contention Interval (1.44 slots)	4,588	1,101	60%
Average Number of Transmissions per packet	1,821	2,767	
Candidate Packet Overhead			982%

From SUO SAS TIM, June 12 & 13 2001

Actual Application Data 1.8 Mbps ≈ 0.9 %

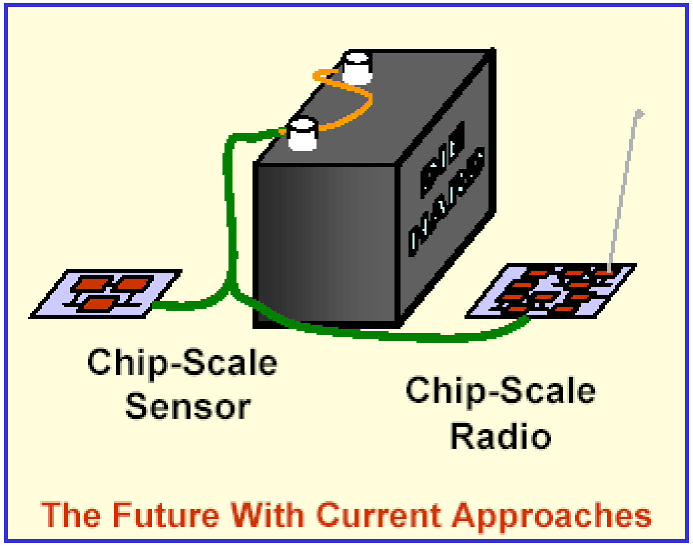
- Does Not Include Initial Acquisition, Other Entry Requests, TCP, Routing Table, and Related Bandwidth Requirements
- 10 Second Set-up Time Represents Opportunity Cost of 2 Gigabits of Throughput

(DARPA Connectionless Networks)

→Motivates cross-layer design
→Architecture vs. Performance

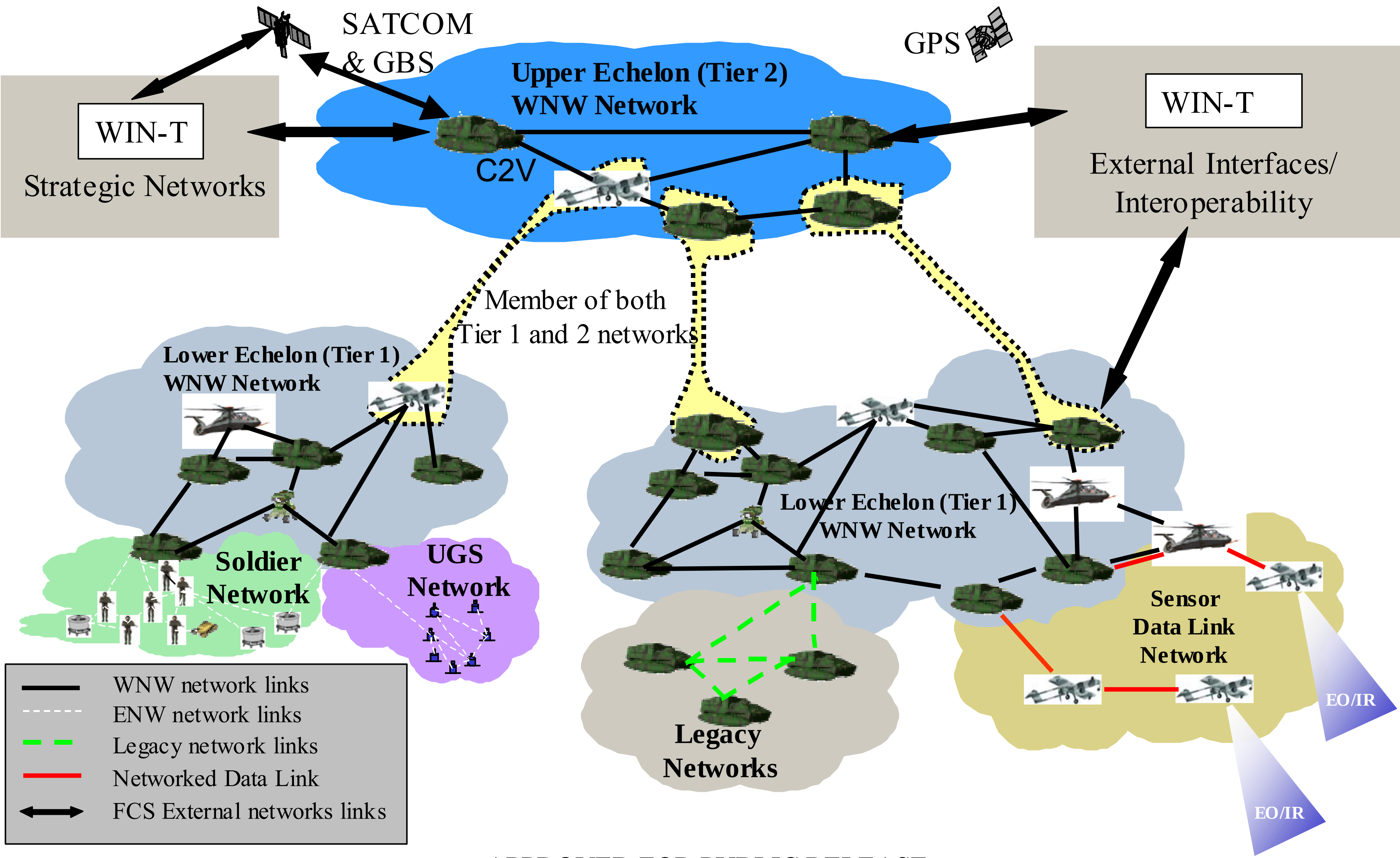
Low Duty-Cycled Sensor Network Demands

Different Kind of Radio



- ✓ Energy consumed in ``staying awake''
- ✗ Moore's "law" does not extend to Shannon / Maxwell
- ➢ Motivates cross-layer design

FCS (UOA) Network Communications Architecture



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Outline

- Basic sensor network problems
  Distributed Detection
  Estimation
  PHY-MAC

Some Questions:

- What makes a sensor network different?
- Current methodologies / architectures adequate?
- What are the challenges ?

- Who owns / controls the sensor ?

- Who has access to the sensor ?

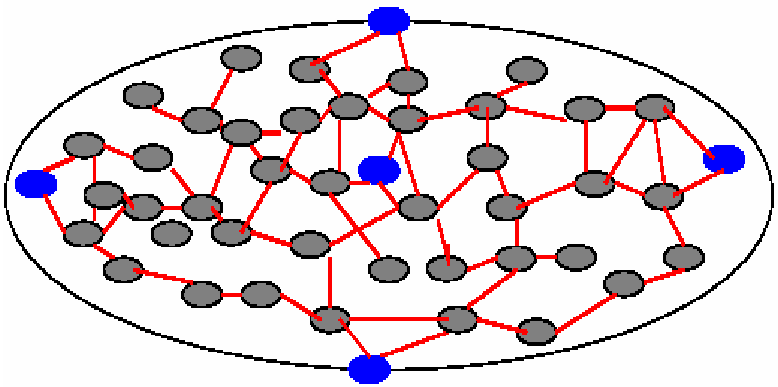
- How may sensors are alive? For how long?

- Should sensors talk to each other : how much ?

- **MAC issues**:
  - Nodes may have only one packet to send (no stability issue)
  - Nodes have finite battery : listening consumes energy
  - `Send when the channel is good'
  - How to control sensors

➢ **Motivates judicious cross-layer design**

Large Scale Sensor Networks



Applications:

- Infrastructure security / area denial
- Traffic control
- Habitat monitoring
- Target detection / tracking
- Chem-bio-Rad detection
- DSN, SensIT, Rembass, TRSS, CEC, FDS, ADS, SoSuS

Nodes:

- Randomly deployed
- Many nodes, wide area
- Low power, low duty cycle
- Low cost and complexity
- Asynchrony

Network:

- Peer-to-peer or Hierarchical ?
- Packets to/from gateway nodes
- Gateways may be mobile
- Correlated / asymmetric traffic

Channel :

- Fading, path loss; NLOS
- CCI / CSI; Jamming

→ **Interplay between sensing, SP, comms and control**

→ **Data-centric paradigm**

One Hop or Multi-Hop

Transmitting one bit: $E_{tx}(r) = e_{tx} + \max\{e_{min}, e_{out} r^{\alpha}\}$.

Hardware limit on r: $r \geq r_0 = (\frac{e_{min}}{e_{out}})^{\frac{1}{\alpha}}$

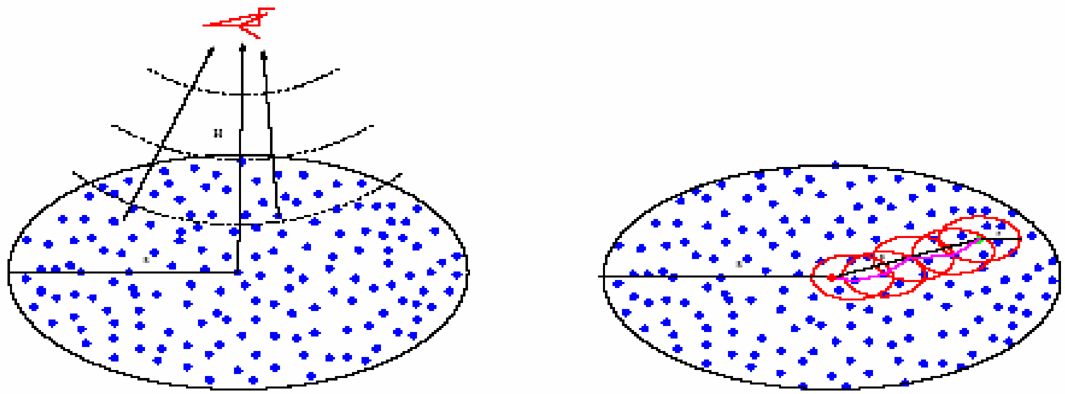
Energy consumption in one hop

$$\mathcal{E}_1(r) = E_{tx}(r) + (\frac{r^2}{R^2}(N-1))E_{rx}$$

Minimum Transmission Range

$$r \;\; \geq \;\; r_{min} \triangleq \max\{r_0, R\sqrt{\frac{\log N}{N}}\}$$

Energy efficiency: a case for mobility



$$\mathcal{E}_{\text{SENMA}} = E_{\text{tx}}(H) = \mathcal{O}(1)$$

$$\mathcal{E}_{\text{AdHoc}} = \begin{cases} \mathcal{O}(\sqrt{N \log N}) & \rho \uparrow, \ r_0 = 0 \\ \mathcal{O}(N) & \rho \uparrow, \ r_0 > 0 \\ \mathcal{O}(\sqrt{N (\log N)^{\alpha-1}}) & R \uparrow \end{cases}$$

Remark

If $\mathcal{O}(\sqrt{N})$ number of packets are to be extracted, then energy consumption per node is unbounded as $N \to \infty$ without perfect scheduling!

→ Listening / Routing dominates energy consumption

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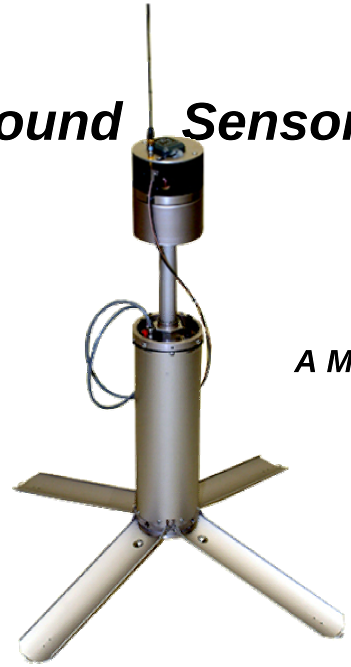
SOME SENSORS

UGS: *Unattended Ground Sensor Array*

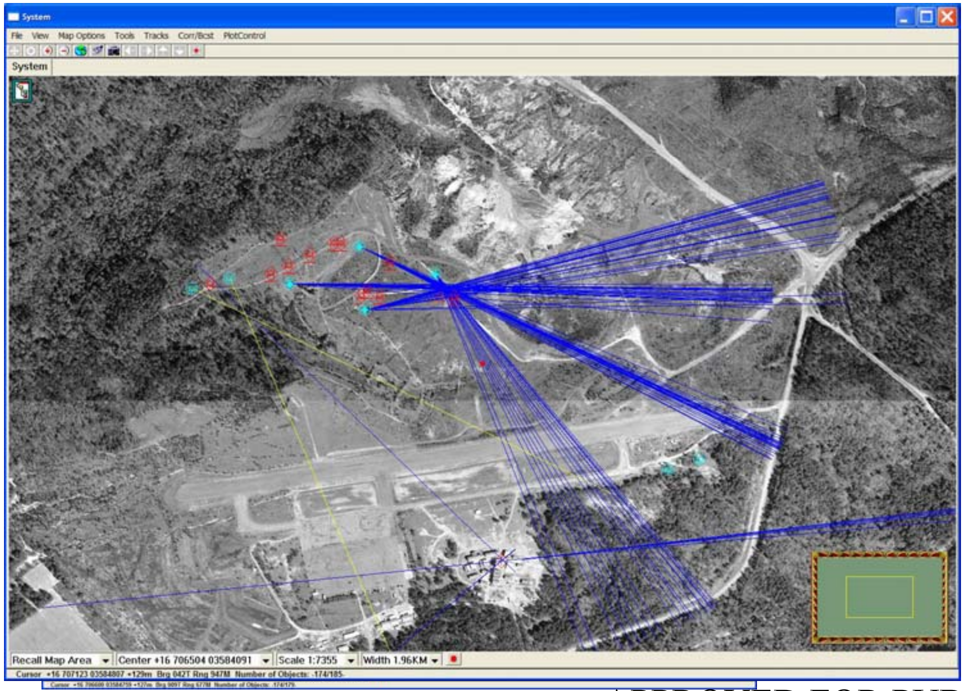
Mortar Detection



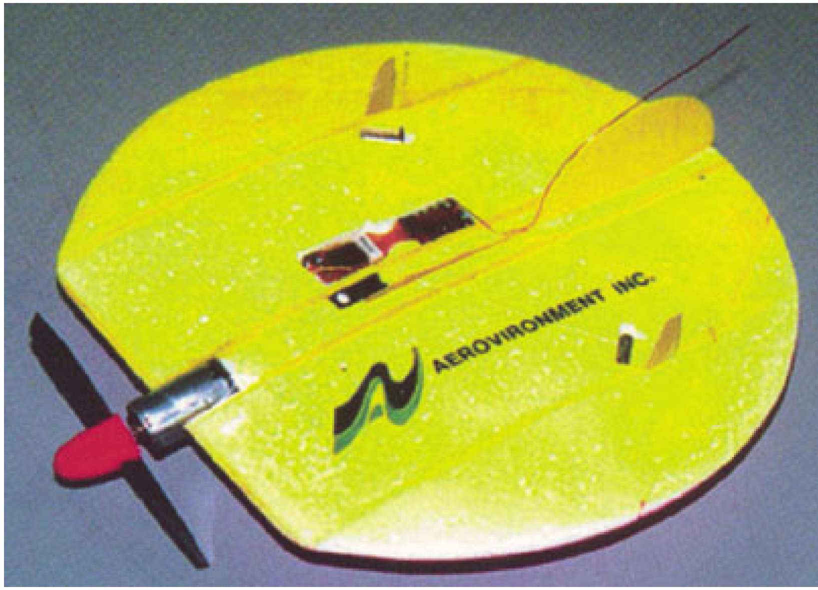
A MAIS sensor

IR Trip wire

Acoustic Array



An UGS array of IR nd acoustic sensors track a convoy. .



PACBOT

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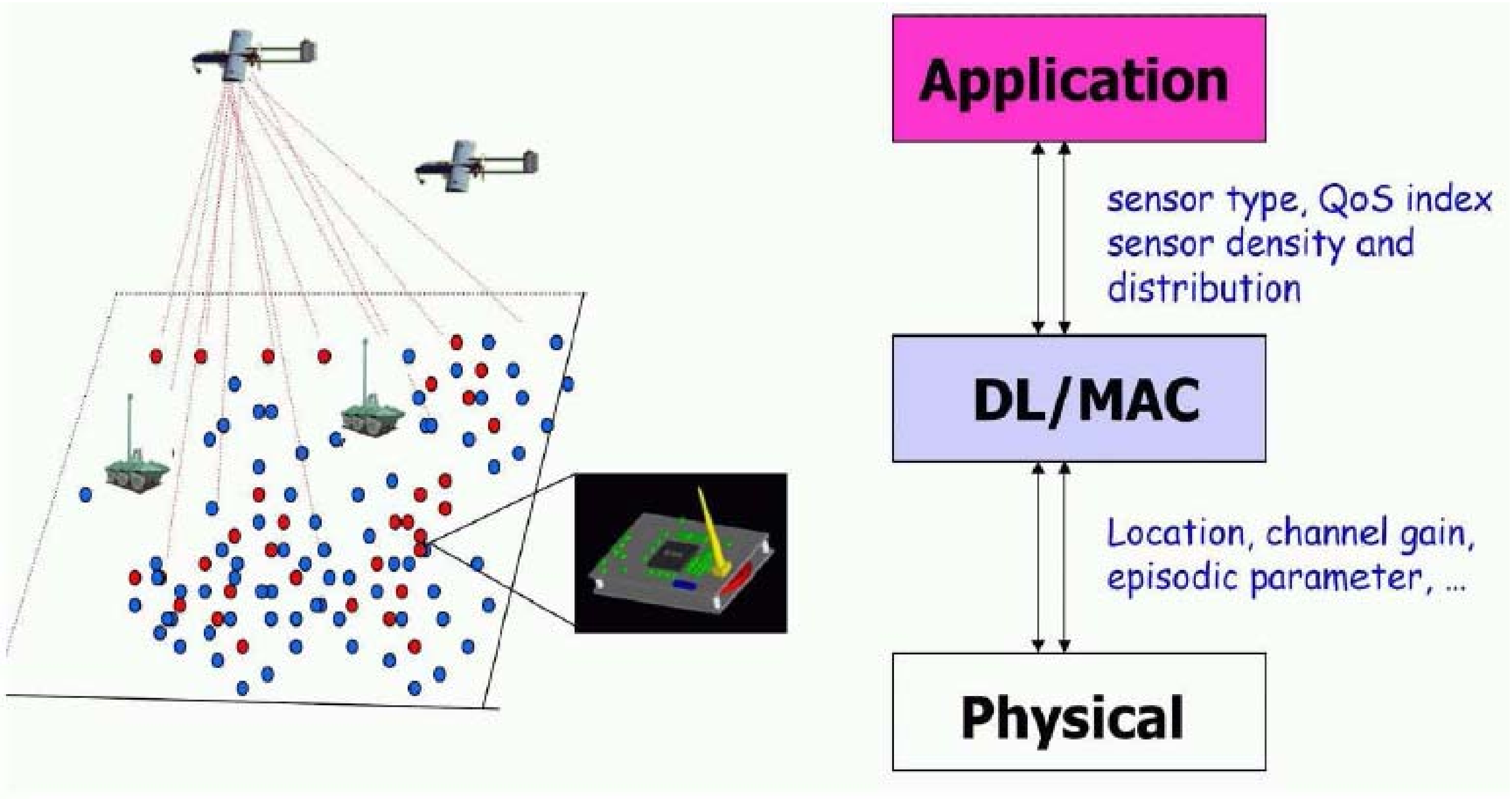
Cross-Layer Design with Mobility



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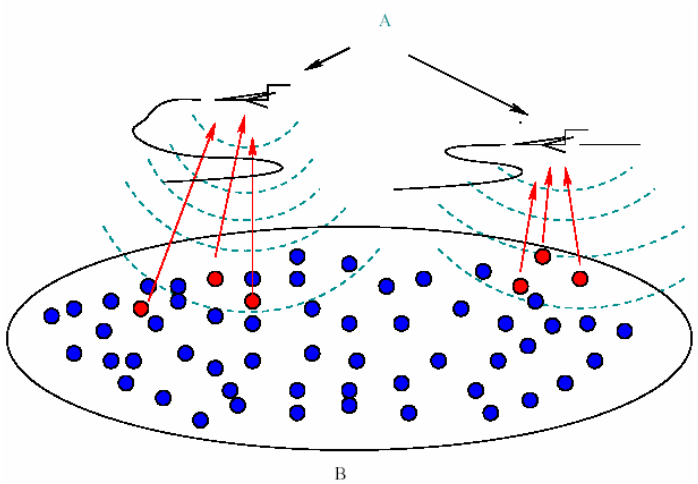
  Estimation

  PHY-MAC

Example 1: (Distributed) Detection



- ☑ Optimal fusion rule?
- ☑ Optimal local threshold?
- ➢ (APP-MAC-PHY interaction)
- ✖ How many bits per sensor ?
- ✖ Identical sensors?
- ✖ With correlated data?

Approach:

- *Local* problem: θ ~ 0
- *Asymptotic:* Many sensors
- *Randomly* distributed sensors
- *Marked thinned IPP*

- $\mathbf{Y_i = W_i + \theta\, s(X_i)}$: W iid
- Binary sensors
- RA channel

[STS, 2004]

Non-Randomized ALMP Global Detector

- Optimal Fusion Rule: Decide H_1 ($\theta > 0$) if $\Delta_{n,o} > Q^{-1}(\alpha)$

  $\Delta_{n,o} = [\ \Sigma_A\ s(x_i) - n\ \lambda_o \int_A s(x)\ dx\ ] \,/\, [n\ \lambda_o \int_A s^2(x)\ dx\ ]^{1/2}$

- Power under fixed global size:

  $\rightarrow Q(\ Q^{-1}(\alpha) - \theta[\ n\lambda_h\, p_m\, [\beta'(0;\ \tau_o)]^2 / \beta(0\ ;\ \tau_o) \int_A s^2(x)\ dx\ ]^{1/2}\ )$

- Optimal local threshold: $\tau_{opt} = \arg\max\ \{[\beta'(0;\ \tau)]^2 / \beta(0\ ;\ \tau)\}$

- **For AWGN channel:** $\tau_{opt} = 0.612\ \sigma_w$

  → local size = 0.27 : `poor' sensors

- Error decreases exponentially in "SNR"
- Build a better MAC? Increase sensor density?

  $\lambda_o = \lambda_h\, p_m\ \beta(0\ ;\ \tau_o)$

- → $n\ p_m$ must increase with n :

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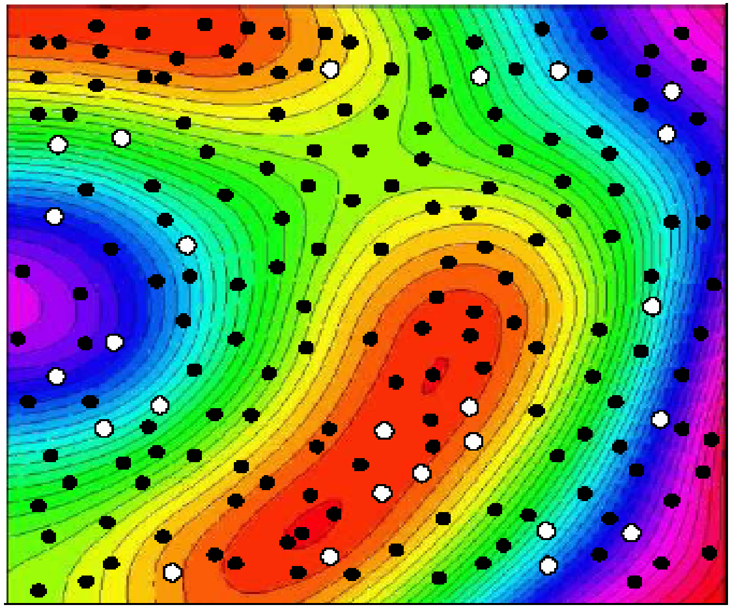
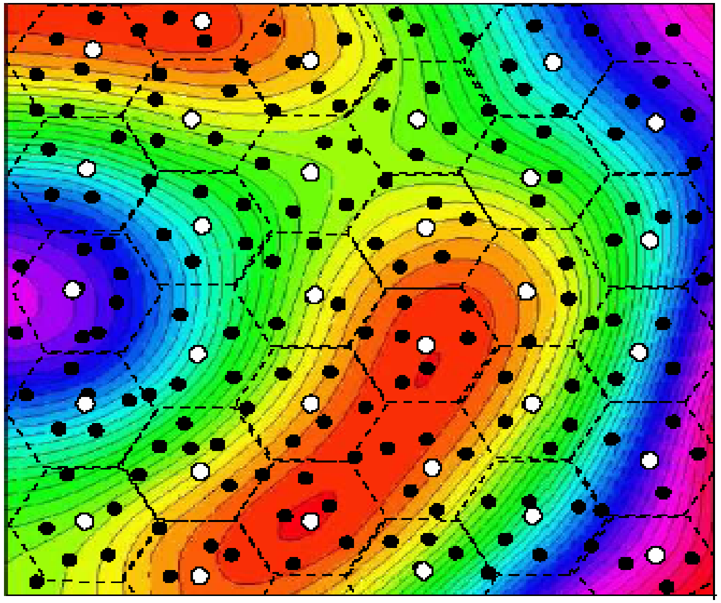
Impact of MAC on Estimation



Random Access



Deterministic Scheduling

Which MAC is preferable?

Random or Regular Sampling ?
Random Access or Scheduling ?

Assumptions:

- Dense network; sensors know locations
- AR(1) model for data : `interpolation'
- Metric: Expected Maximum Distortion
- Random access needs O (log K) more packets;
  has O(log K) higher excess MSE:

$$\mathbf{M_D = O\ (\ M_R \,/\, \ln M_R)}$$

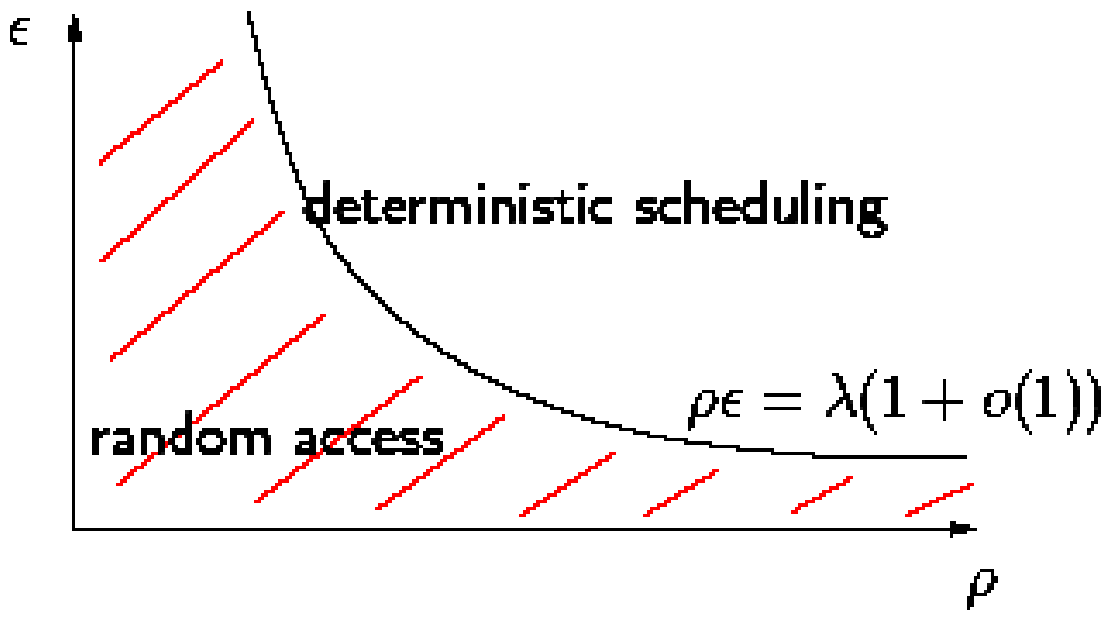
$$\mathbf{r(K,SNR) = \ln\ (K) + O(\ ..)}$$

Should we always schedule ?

[DTS, 2003]

3. Estimation: Finite Density Networks

- DS: sensor may not exist
- RA: Collision channel



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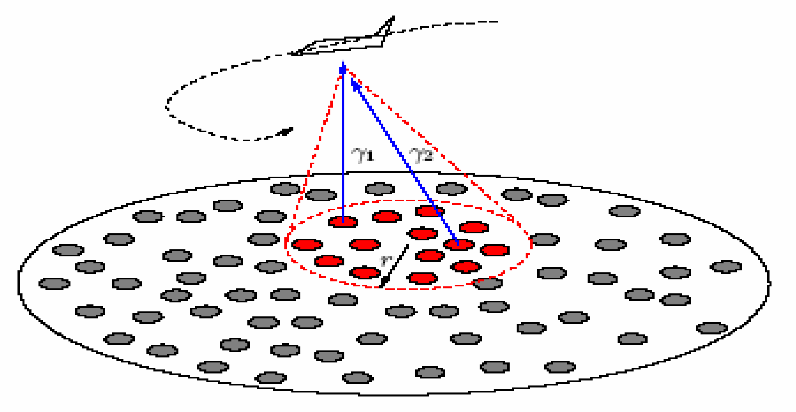
Opportunistic MAC



Distributed Opportunistic MAC

- ☐ Channel Acquisition
  Estimate γ from beacon.
- ☐ Opportunistic ALOHA
  Transmit with probability $s(\gamma)$.
- ☐ Opportunistic CSMA
  - ☐ Sense carrier with backoff $\tau(\gamma)$.

- Mobility induces fading
- Wait for a good channel

Advantages

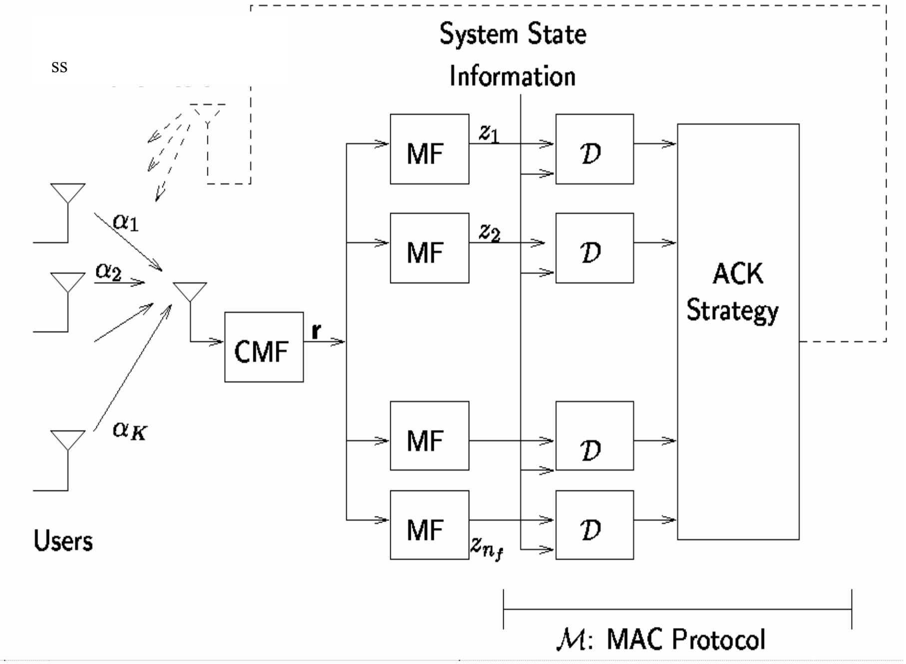
☐ Simplicity. ☐ Scalability.

☐ Energy Efficiency.

- Transmit with probability based on CSI : O-ALOHA

[VAT 2004; ZT 2004]

Example 4: Optimal Detection for MAC



Optimal Detection at the Receiver:

- MAC assumes accurate detection of requests.
  - RTS-CTS exchanges. Busy-tone detection.
- Missed detections and false alarms likely in interference-rich environment

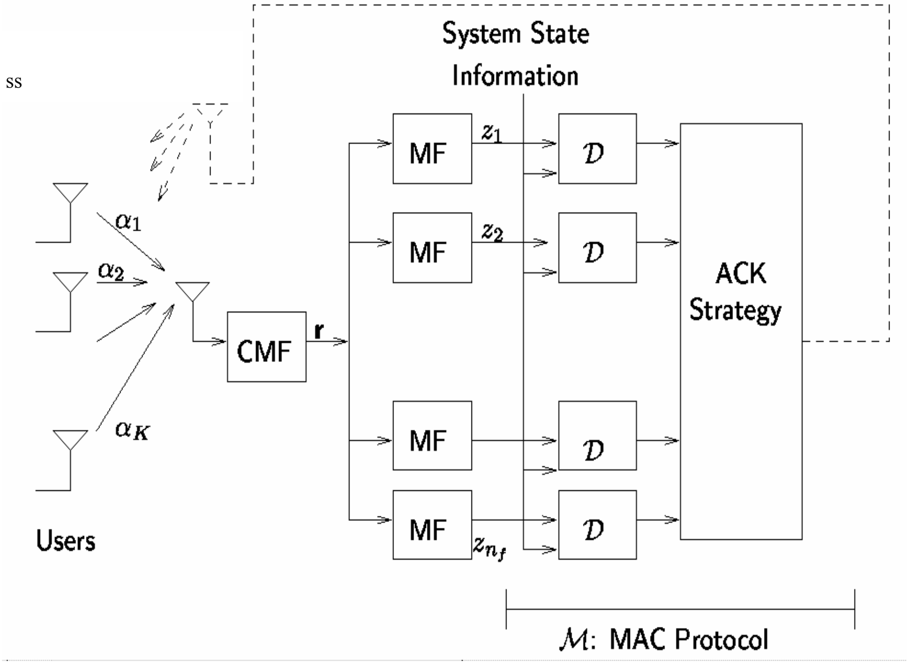
  What is the impact on the MAC?

  How do we model PHY / MAC interaction ?
- What is the detector that optimizes the MAC performance (throughput and delays)?

➢ Markov chain formulation / Optimal Bayesian detector

[MTS, 2003]

Signal Model



Users select random codes
Unknown fades

N = # orthogonal codes
f = # free codes
L = packet length
λ = arrival rate

MF output is a sufficient statistic: $\sim$ CN$(0, K_i\,\sigma^2 + \sigma^2_v)$ K is unknown.

Traffic: Poisson w aggregate rate λ → K is Poisson (λ /f)

PHY-MAC problem: K = 1 ? Metric ?

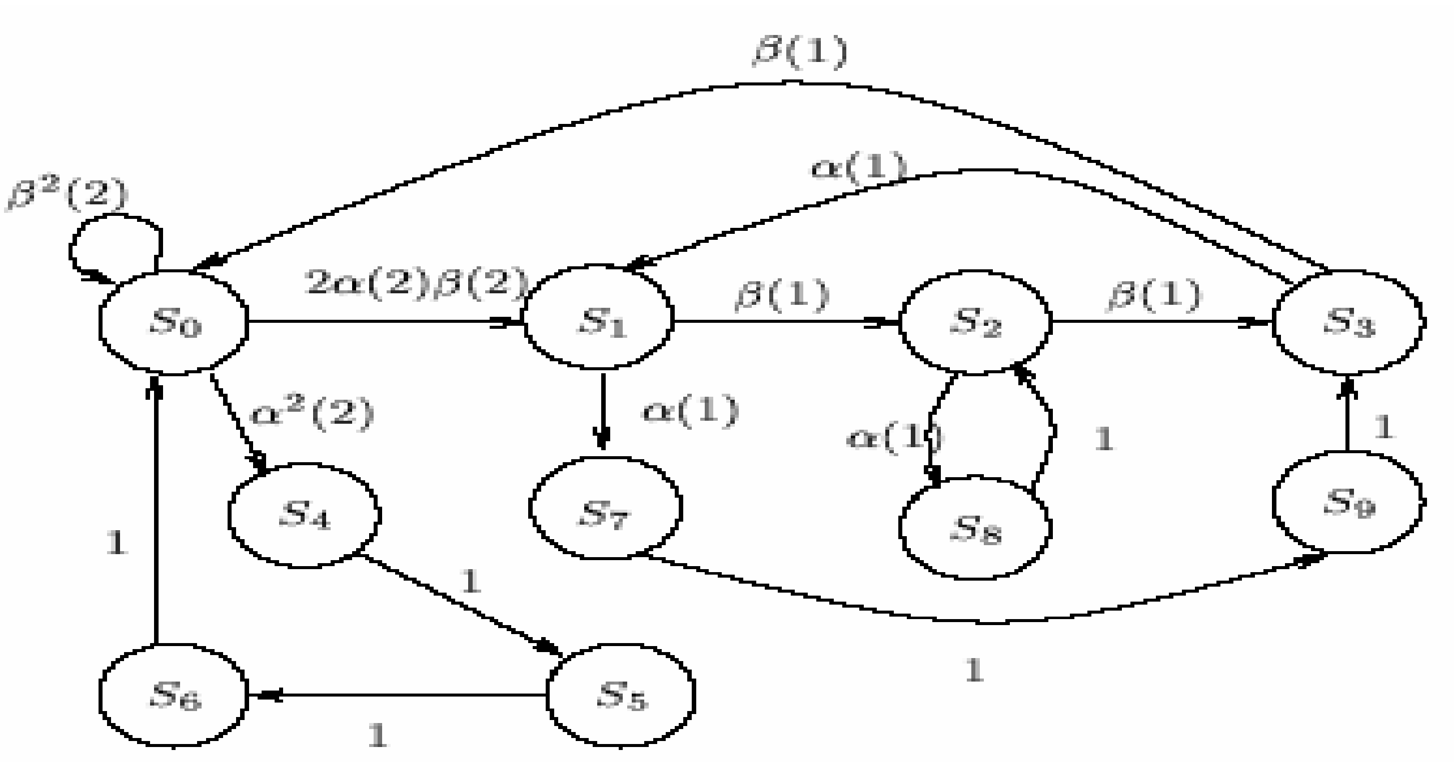
Two Approaches:

- Optimal detection + optimal scheduling
- Joint optimization to maximize throughput

Markov Chain for N=2, L=3

$\alpha(f)$ = Prob of ACK'ing a channel, given *f* free channels

$\beta(f) = 1 - \alpha(f)$

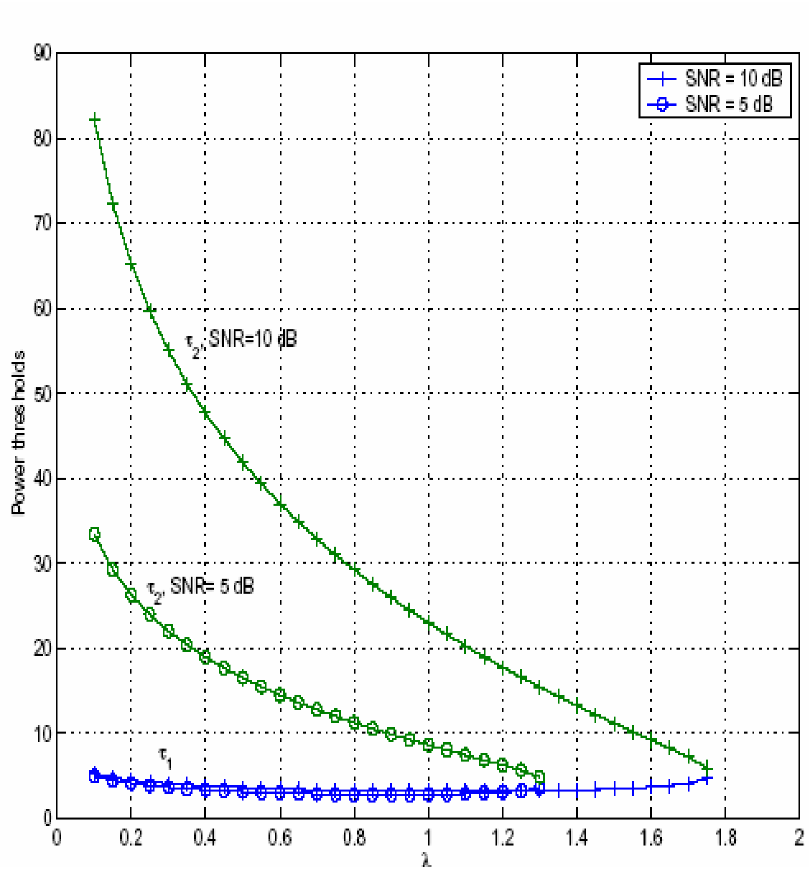


Symbol	State	f_i
S_0	[0 0 0]	2
S_1	[0 0 1]	1
S_2	[0 1 0]	1
S_3	[1 0 0]	1
S_4	[0 0 2]	0
S_5	[0 2 0]	0
S_6	[2 0 0]	0
S_7	[0 1 1]	0
S_8	[1 0 1]	0
S_9	[1 1 0]	0

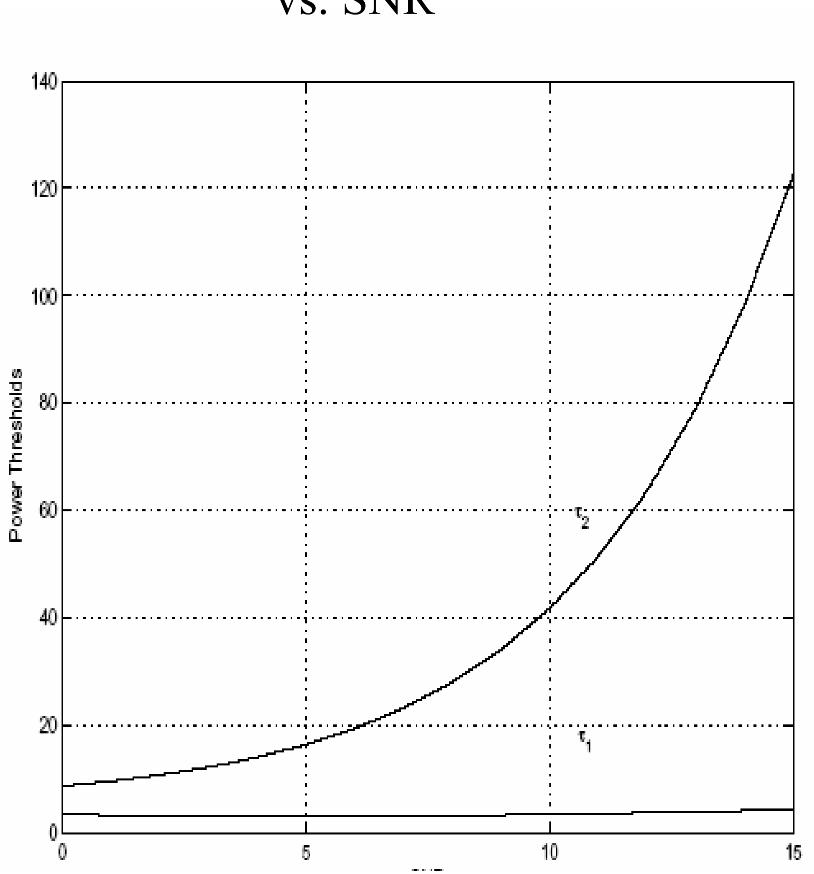
* ¥ N,L, Markov chain is finite, aperiodic, and irreducible → Sty distro π_δ exists

Optimal Decision Regions

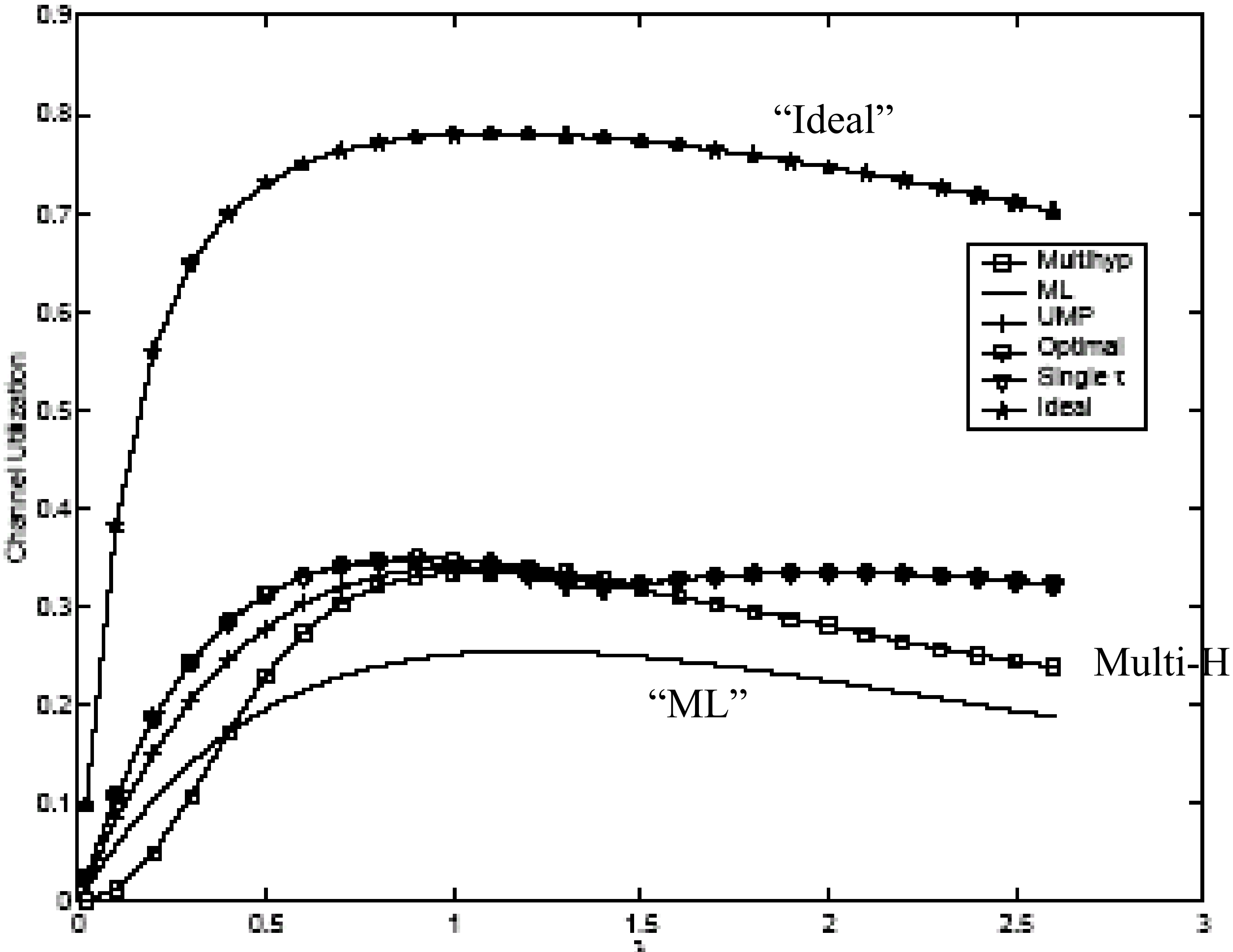
vs. arrival rate



vs. SNR

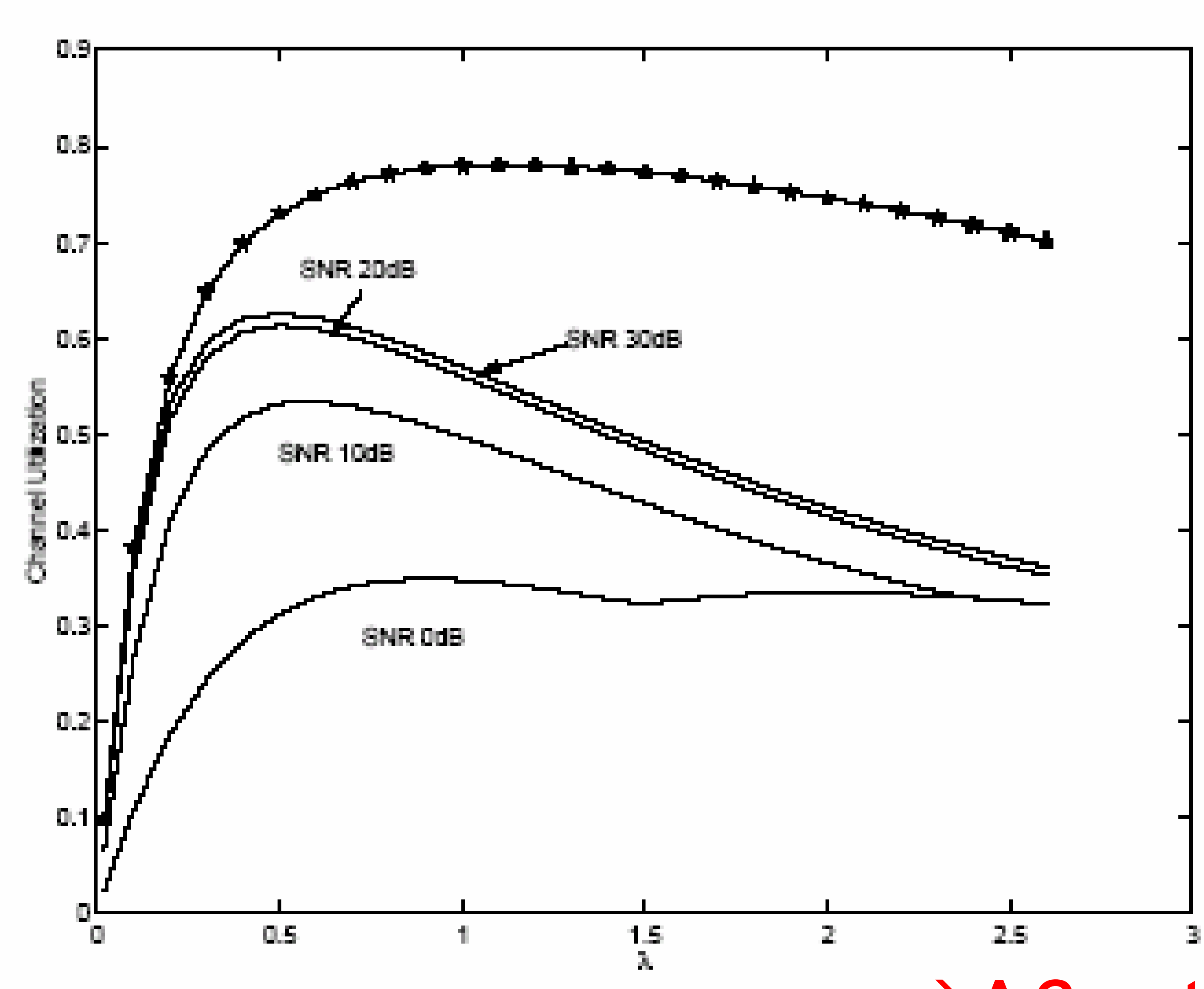


Utilization vs. Traffic Rate



→ **Cross-Layer Design is effective at low SNR's**

Utilization Curves



→ **A Gap still exists**

Cross-Layer Design

- promises adaptibility, agility, efficiency.
- Does not always imply improved performance.
- Potential for instability
- Sensor networks are application specific; PHY+MAC+APP cross-layering natural.

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